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Long-term tillage effects on the distribution of P fractions of German loess soils

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1 Introduction

In soil, phosphorus (P) exists in many different organic (P_o) and inorganic (P_i) forms, whereas only a small part of P_i is plant available (Redel et al., 2007). In order to adjust P fertilization to plant demand, information about the availability of P is required. In agri-cultural systems, crop management has a strong effect on the soil P content and P availability.

Tillage influences physical and chemical processes in soil (Vu et al. 2009) and may therefore also affect the retention and stabilization of P (Wright, 2009). Intensive tillage may decrease soil organic matter content and soil structure compared to reduced tillage (D'Haene et al., 2008), potentially reducing P_o and resulting in increased P losses through different aggregate dynamics, erosion and runoff (Scholz et al., 2008). Tillage also mixes the soil to a certain depth, preventing a stratification within the tilled soil layer and affect the carbon depositions (Vu et al., 2009).

The results of several studies highlight the need to divide the soil profile into different layers as the effect of the tillage system and therefore the incorporation of organic matter on P pools may depend on depth. The objectives of this study were to determine the effects of long-term tillage practices on P availability and the distribution of organic and inorganic P fractions in the soil profile; and to study the relationship between P fractions and selected physical and chemical soil properties.

2 Materials and methods

Soil was sampled from a long-term field trial, which was initiated at four loess sites (Friemar, Grombach, Lüttewitz, Zschortau) between 1990 and 1997 by the Institute for Sugar Beet Research, Göttingen (IfZ) in cooperation with the agricultural division of Südzucker AG in eastern and southern Germany.

Soil texture varies with clay contents ranging from 15% to 30%. The sand content is below 6%, except at Zschortau (26%). At all sites, crop rotation was two years of winter wheat (*Triticum aestivum* L.), followed by sugar beets (*Beta vulgaris* DÖLL). Crop residues were left in the field.

At each location a field has been divided into two strips, one has been under CT (mouldboard ploughing to a depth of 25-30 cm), while the other has been under NT (no cultivation, except for seedbed preparation for sugar beet sowing to a depth of 5 cm).

Mineral fertilizers (N, P, K and Mg) and calcium carbonate were applied according to site specific recommendations and rates were identical for the two tillage treatments at each site (Koch et al., 2009).

Field-moist soil samples were used to determine the different P fractions following the sequential extraction method by Hedley et al. (1982). Amorphous iron (Fe_{ox}) and aluminium (Al_{ox}) was extracted following the DIN-method 19684-6. CAL-extractable P (CAL-P) was determined by the DIN method DIN EN ISO 11885.

3 Results and discussion

Soil organic carbon contents decreased with sampling depth, however, the difference was only significant under NT, where C_{org} reached 17.8 g kg^{-1} in the top 5 cm of the profile, while it was only 6.2 g kg^{-1} in the layer between 25 and 40 cm. Under CT the decrease with depth (from 11.1 to 8.1 g kg^{-1}) was much less pro-nounced).

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Oxalate-extractable Fe and Al contents were similar in all depths and slightly higher under NT than CT, averaging 1.56 and 1.75 g Fe_{ox} kg^{-1} soil, and 0.67 and 0.71 g Al_{ox} kg^{-1} soil in the soils under CT and NT, respectively.

The winter wheat and sugar beet yields of the four sites, averaged from 2004 to 2010, are mostly higher (1 to 23% higher) compared to the mean yields of Germany (75 dt ha^{-1} winter wheat, 605 dt ha^{-1} sugar beets).

The P status for all sites ranged from 15 to 58 mg CAL-P kg^{-1} soil. At Friemar, Lüttewitz and Zschortau the P contents under both treatments were attributed to class B (Friemar and Lüttwitz) and C (Zschortau) of the VD-LUFA ranking thus the P supply at Friemar, Lüttewitz and Zschortau was sufficiently. At Grombach, with 15 and 17 mg CAL-P kg^{-1} in the soils under CT and NT, respectively, the required P content for a normal growth of the crops is not directly provided (VD-LUFA class A). However, according to the modified system of Köster and Nieder (2007), all sites ranged in the CAL-P content classes B and C, so a sufficient P supply was warranted. The grain and taproot yields which were similar for all four sites and in the range of the German average suggested that P limitation was not present at Grombach.

The CAL-P content was negatively correlated with the Al_{ox} content (r=-0.53) and showed a positve correlation with the C_{org} content (r=0.46), suggesting that CAL-P is not bound to amporphous Al but to organic matter. This was also true for both labile P fractions, which were additional well correlated with total N content (r=0.54 and r= 0.51 for DI-P and $NaHCO_3$, respectively).

The labile P content was highest for the upper 5 cm in soils under NT compared to CT and decreased with sampling depth for both treatments, whereas below the top 5 cm, the differences between tillage treatments were minimal (Figure 1). This was also reported by Zamuner et al. (2008) for a clay loam. The most labile P fraction, extracted in their study with an anion exchange membrane, was closely related to C_{org} contents. They concluded that P availability is mainly controlled by P_o. Our results support this conclusion, since a significant proportion of the variability (52%) of the most labile P_i fractions (DI-P and $NaHCO_3$-P) was explained by C_{org} (Table 2) by models selected by stepwise multiple regression and there was also a strong correlation between both labile fractions and total N content (r=0.54 and r=0.51 for DI-P and $NaHCO_3$, respectively) and between DI-P and C_{org} content (r=0.55).

Table 1: Means, standard deviations and significance values of P-fractions (n=4). Values followed by the same letter are not significantly different (P<0.05). Capital letters refer to the comparison of tillage treatments, while lower case letters refer to sampling depth

		Contents [mg P kg^{-1}]			Stocks [kg ha^{-1}]
P fraction	Tillage treatment	0-5 cm	5-25 cm	25-40 cm	0-40 cm
Water extractable P (DI-P)	CT	9.2 (1.1) A	10.2 (0.7)	7.4 (1.9)	46.8 (6.0)
	NT	15.8 (1.7) Ba	8.6 (1.1) b	5.6 (1.7) b	45.8 (6.7)
Bicarbonate soluble P_i ($NaHCO_3$-P_i)	CT	36.5 (4.8)	34.7 (4.2)	29.3 (4.9)	171 (22)
	NT	48.3 (5.0) a	35.7 (2.4) ab	23.2 (4.5) b	181 (17)
Bicarbonate soluble P_o ($NaHCO_3$-P_o)	CT	55.8 (7.9)	71.3 (10.7)	60.2 (8.9)	341 (22)
	NT	64.2 (8.6)	66.6 (9.0)	56.5 (7.8)	352 (43)
Hydroxide soluble P_i (NaOH-P_i)	CT	93.4 (10.3)	91.9 (10.1)	79.1 (10.3)	454 (50)
	NT	114 (21)	100 (13)	77.2 (10.2)	523 (73)
Hydroxide soluble P_o (NaOH-P_o)	CT	93.4 (10.2) A	97.9 (6.3)	92.0 (9.9)	496 (32)
	NT	133 (2) Ba	105 (8) a	64.5 (13.3) b	517 (27)
Hydrochloric acid soluble P (HCl-P)	CT	152 (19)	158 (17)	141 (25)	787 (108)
	NT	161 (18)	153 (21)	137 (35)	837 (155)
Residual-P	CT	250 (28)	237 (28)	213 (28)	1198 (141)
	NT	256 (28)	229 (31)	210 (32)	1262 (169)
P_i	CT	541 (53)	532 (45)	470 (56)	2656 (260)
	NT	595 (65)	527 (49)	453 (49)	2849 (298)
P_o	CT	149 (17)	169 (15)	152 (4)	837 (51)
	NT	197 (7) a	172 (14) ab	121 (21) b	869 (68)
P_t	CT	691 (59)	701 (50)	622 (58)	3493 (275)
	NT	792 (68)	698 (45)	574 (68)	3719 (343)

Next to the C_{org} content Fe_{ox} was the most important variable related to the labile P_i fractions (Table 2). This suggests that at least some of the P was only weakly sorbed. Oxalate mainly removes amorphous forms of Fe and Al, which have large surface areas and have generally found to be important in P sorption

(Borggard et al., 1990). The relative contribution of Fe and Al to P sorption is soil specific and mainly depends on the degree of crystallization (Borggard et al. 1990). Freese et al. (1982) reported for a number of German soils with clay contents of less than 1 to 22% that both Fe_{ox} and Al_{ox} were the important parameters determining P sorption.

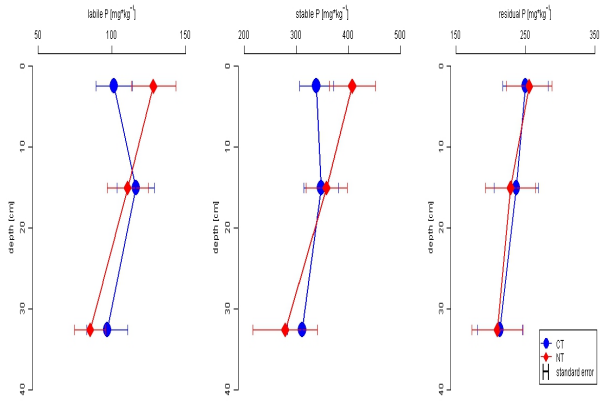

Figure 1: Labile (DI-P and $NaHCO_3$-P_t), stable (NaOH-P_t and HCl-P) and residual-P in the soil profile under conventional tillage (CT) and no-till (NT). Error bars refer to standard error (n=4).

The stable P contents were similarly distributed in the soil profile as the labile P contents with the highest contents in the upper 5 cm under NT compared to CT (Figure 1), however, the contents of stable P in CT and NT were three times higher than the contents of labile P. In contrast to labile P content, C_{org} was only weakly related to the stable P fractions (Table 2). Even though C_{org} contributed significantly to NaOH-P_o in the multivariate regression analysis, C_{org} was a poor predictor of NaOH-P_o, as the equation only explained 19% of the variability in NaOH-P_o. In contrast to our results, studies generally found that C_{org} and P_o were correlated (Tiessen et al., 1984 (n=168); Burt et al., 2002 (n=21)). Our results suggest that organic fractions with different C to P ratios contributed to P_o at our sites and that the contribution of these organic fractions to P_o depended on tillage, depth, and/or site. A large proportion of P_o may have been associated with the light fraction, which consists of barely decomposed organic material not associated with the soil mineral fraction. This assumption would also explain why clay, Al_{ox} and Fe_{ox} only explained a small proportion of the variability in P_o.

Table. 2: Stepwise multiple regression analysis of P fractions (expressed in mg kg^{-1} soil) on soil properties, including clay content (clay; g kg^{-1} soil), oxalate extractable Fe (Fe_{ox}; mg kg^{-1} soil), oxalate extractable Al (Al_{ox}; mg kg^{-1} soil), organic C (C_{org}; g kg^{-1} soil), carbonate-C (CO_3-C; g kg^{-1} soil) and pH. Unit of intercepts is mg kg^{-1} dry soil. Abbreviations are explained in Table 1.

	Equation					R^2
DI-P =	-5.28	- 0.012 clay P=0.08	+0.0047 Fe_{ox} P<0.0001	+0.90 C_{org} P<0.0001		0.52
$NaHCO_3$-P_i =	-13.8	+0.017 Fe_{ox} P<0.0001	+1.89 C_{org} P<0.0001			0.52
$NaHCO_3$-P_o =	323	- 20.4 pH P=0.09	- 0.11 Al_{ox} P=0.001	- 0.028 Fe_{ox} P=0.01		0.17
NaOH-P_i =	249	- 29.8 pH P<0.0001	+0.18 clay P=0.0003	- 0.057 Al_{ox} P=0.01	+0.020 Fe_{ox} P=0.002	0.54
NaOH-P_o =	153	- 0.13 Al_{ox} P=0.001	+3.26 C_{org} P=0.03			0.19
HCl-P =	446	- 48.6 pH P<0.0001	+0.15 clay P=0.01	+12.9 CO_3-C P<0.0001		0.47
Residual-P =	138	+0.73 clay P<0.0001	- 0.10 Al_{ox} P=0.07			0.45

The averaged P content for 0-40 cm, HCl-P as one part of the stable P fraction amounted for 22.5% of P_t, each for CT and NT and is believed to consist mainly of Ca-associated P (Hedley et al., 1982). Our study supports this conclusiom, as carbonates explained a significant proportion in the variability of HCl-P in the multivariate model (Table 2). This is in line with Tiessen et al. (1984) and Roberts et al. (1985). This relationship suggests that the behaviour of Ca-carbonates and Ca-phosphates were similar and that Ca play a role in the stabilization of P (Mattingly, 1975).

Stable P is converted into labile P during soil pedogenesis, tranformations and solubility processes and also influenced by fertilization. A large amount of soluble or productive P fertilizers are changed quickly into P compounds on Al and Fe oxides or oxihydrates and on clay mineral surfaces (Werner and Trimborn, 2008).

The distribution of residual-P in the soil profile was equal for CT and NT and decreased slightly with soil depth. This is also true for the residual-P content, which is in the same range under NT and CT. Our results are in line with Wright (2009) and Vu et al. (2009).

As expected, the tilling intensity had no effect on the most stable P fraction which

was displayed by the similar residual-P contents under NT and CT. However, the clay content was a significant factor for HCl-P and residual-P in the multivariate analysis (Table 2). The strong correlation between residual-P and clay content in our study (r=0.69) was also reported by Tiessen et al. (1984). The Fe_{ox} and Al_{ox} contents did not explain a significant proportion of the variability of these two P fractions (Table 2), since oxalate extracts mainly amorphous P. In general, the stable P fractions, namely NaOH-Pi, HCl-P and residual-P, were mainly associated with soil constituents which were little affected by the tillage treatments. As these fractions accounted for two thirds of P_t, tillage could not have a large effect on P_t.

4 Conclusions

No-till slightly increased the soil P content compared to CT, which was mainly due to an increase in labile P in the topsoil. This labile P content was well correlated with the C_{org} content, which suggests that the mineralization of organic matter provides available P.

The incorporation of organic residues in the CT treatments resulted in equal P contents through the soil profile. In the NT treatments, there was a gradient along the depth due to a higher P content in the surface soil, caused by a high C_{org} content in the upper 5 cm.

Labile P content was controlled by C_{org}, while stable P contents depended on the clay content and on Fe_{ox} and Al_{ox}.

In general, the tillage treatment had little effect on P fractions and P availability. Therefore, for the climatic conditions and soil types prevalent at our study sites, factors other than P availability will determine the success of a tillage system.

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